About the initial mass function and He II emission in young starbursts

Daniel Schaerer[1,2,3]

ABSTRACT

We demonstrate that it is crucial to account for the evolution of the starburst population in order to derive reliable numbers of O stars from integrated spectra for burst ages $t > 2-3$ Myr. In these cases the method of Vacca & Conti (1992) and Vacca (1994) *systematically underestimates* the number of O stars. Therefore the current WR/O number ratios in Wolf–Rayet (WR) galaxies are overestimated. This questions recent claims about flat IMF slopes ($\alpha \sim 1$–2) in these objects. If the evolution of the burst is properly treated we find that the observations are indeed compatible with a Salpeter IMF, in agreement with earlier studies.

Including recent predictions from non–LTE, line blanketed model atmospheres which account for stellar winds, we synthesize the nebular and WR He II λ 4686 emission in young starbursts. For metallicities $1/5\, Z_\odot \leq Z \leq Z_\odot$ we predict a *strong nebular* He II *emission due to a significant fraction of WC stars* in early WR phases of the burst. For other metallicities broad WR emission will always dominate the He II emission. Our predictions of the nebular He II intensity agree well with the observations in WR galaxies and an important fraction of the giant H II regions where nebular He II is detected. We propose further observational tests of our result.

Subject headings: galaxies: starburst — H II regions — stars: Wolf-Rayet

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[1]Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218

[2]Geneva Observatory, CH-1290 Sauverny, Switzerland

[3]Observatoire Midi-Pyrénées, 14 Av. Edouard Belin, F-31400 Toulouse, France

1. IMF determinations in young starbursts

To derive the initial mass function in starburst galaxies is one of the fundamental goals in studies of starforming regions. Due to their large luminosity, massive stars are directly visible in the integrated spectrum of young starbursts and thereby provide a unique opportunity to study their stellar content. In a subset of emission line galaxies – often referred to as Wolf–Rayet galaxies (cf. Conti 1991) – *broad stellar emission lines* in the optical (most prominently He II λ 4686) testify to an important population of Wolf–Rayet (WR) stars, which are the descendents of the most massive O stars (see e.g. Maeder & Conti 1994). The *nebular emission lines*, on the other hand, are due to the exciting stars present in the starburst including the less massive OB stars. Observations of WR features and nebular lines thus contain information about stars from different mass ranges. WR galaxies therefore in particular offer a unique opportunity to probe the upper part of the IMF in young starbursts.

1.1. Difficulties with the non-evolving cluster approach

Since the first discoveries of WR stars in emission line galaxies by Allen, Wright, & Gross (1976) and Kunth & Sargent (1981), the recent work of Vacca & Conti (1992, hereafter VC92) provides the most detailed quantitative study of the massive star population in WR galaxies. Their technique, developed in more detail by Vacca (1994, hereafter V94), allows to determine the relative number of WR and O stars. Comparisons with stellar evolution models show that the large WR/O ratios can only be explained by *bursts of star formation* occurring over short timescales compared to the lifetime of massive stars (Arnault, Kunth, & Schild 1989, VC92, Meynet 1995).

At first sight the comparison of the WR/O ratios of VC92 and Contini, Davoust, & Considère (1995, hereafter CDC95) with the evolutionary calculations of Meynet (1995), however, seems to show that a *flat IMF slope* ($\alpha \sim$ 1–2, compared to the Salpeter value of $\alpha = 2.35$) is required to explain the observations (Meynet 1995, CDC95)[4]. This result is, however, in disagreement with several other methods, such as direct stellar counts in clusters ($\alpha \sim 2 - 3.1$; cf. Maeder & Conti) and population synthesis techniques (Olofsson 1989, Mas-Hesse & Kunth 1991, Krüger et al. 1992, Vacca et al. 1995), which show that observations of similar (and partly even the same) objects are compatible with a Salpeter IMF over a large range of metallicities.

It can, indeed, easily be traced back why applying the method of VC92 and V94 can lead to erroneously large WNL/O ratios, which would imply a flat IMF. From the ratio of the luminosity in the WR feature to the Hβ luminosity, they derive $N_{\mathrm{WNL}}/N'_{\mathrm{O7V}}$, the number of WNL stars over the number of so-called "equivalent O7V stars", which are required to produce the Lyman continuum flux measured from the Hβ line. They then deduce the ratio of WNL over OV stars from $N_{\mathrm{WNL}}/N_{\mathrm{OV}} = \eta_0 N_{\mathrm{WNL}}/N'_{\mathrm{O7V}}$, where η_0 is the IMF averaged ionizing Lyman continuum luminosity of a population normalized to the output of one "equivalent" O7V star (see V94).

The fundamental assumption entering the derivation of $N_{\mathrm{WNL}}/N_{\mathrm{OV}}$, or equivalently η_0, is that the Lyman continuum luminosity is produced by an *unevolved Zero-Age Main Sequence* (ZAMS) population. Obviously this assumption is not compatible with the presence of WR stars — the descendents of O stars — which clearly indicate ages of typically at least 3 Myr. $N_{\mathrm{WNL}}/N_{\mathrm{OV}}$ therefore denotes the number ratio of WNL stars with respect to a purely theoretical ZAMS OV

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[4]It should be noted that in Fig. 3 of Maeder & Conti (1994) the slope of the IMF has inadvertently been mislabeled, due to a confusion in the notation. Their values of $\Gamma = -1$, and -2 should correctly refer to $\alpha = 1$ and 2 in the above notation, where the Salpeter slope is given by $\alpha = 2.35$. See also the original paper by Meynet (1995) who uses $\alpha = x$.

star population, which: *1)* has no observational correspondence, and *2)* cannot directly be compared to WR/O number ratios derived from evolutionary models.

In an instantaneous burst, due to the evolution of the O star population and the subsequent disappearance of the most massive stars, the number of Lyman continuum photons, Q_0, strongly decreases after 2–3 Myr. This is illustrated in Fig. 1, where we plot the time evolution of

$$\eta_0\left(t\right) = \frac{\int_{M_{\mathrm{low}}}^{M_{\mathrm{up}}} \Phi\left(M\right) Q_0\left(M, t\right) dM}{Q_0^{\mathrm{O7V}} \int_{M_{\mathrm{O}}}^{M_{\mathrm{up}}} \Phi\left(M\right) dM}, \qquad (1)$$

with respect to its ZAMS value $\eta_0(t=0)$ in an instantaneous burst. Following V94, Φ is the IMF with the mass limits M_{low} and M_{up}, $Q_0\left(M, t\right)$ is the ionizing luminosity as a function of initial mass and time, and $\log Q_0^{\mathrm{O7V}} = 49.05$. The integral in the denominator counts the number of O stars defined as having $T_{\mathrm{eff}} \geq 33000$ K.

The strong decrease of η_0 after ~ 2 Myr implies that the required *number of O stars will be systematically underestimated* (and hence the WR/O ratio overestimated) if one does not account for the evolution of the population and uses the ZAMS values of a "non-evolving cluster". For younger ages the approach of V94 should, however, be valid. At the low metallicities typical of the objects from VC92, the decrease of η_0 in the WR rich phases (see Fig. 1) implies that the quantity $N_{\mathrm{WNL}}/N_{\mathrm{OV}}$ overestimates the real WNL/O ratio by a factor of 1.1 to 7.4, depending on the exact age of the burst. As can be seen from Meynet (1995, Fig. 6), such a decrease of the WNL/O ratio allows an important steepening of the IMF slope, which may bring the values closer to a Salpeter-like IMF.

The possible difficulty of determining the number of O stars from η_0 for "evolved" populations was already mentioned by V94. One could in principle account (to first order) for the evolution by simply lowering the upper mass limit to the value of the present-day mass function. Such
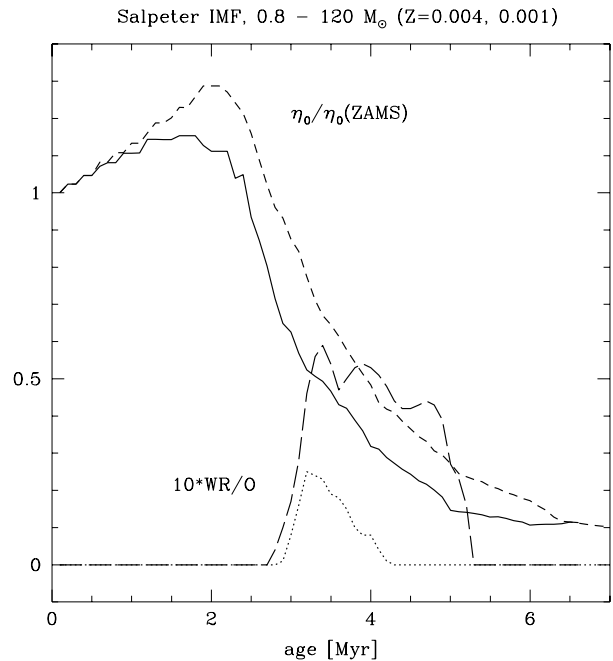

Fig. 1.— Time evolution of η_0 (solid and short-dashed line) in an instantaneous burst for Z=0.004 and 0.001 respectively. A Salpeter IMF from 0.8 to 120 $M_\odot$ is assumed. To indicate the time occurrence of the WR phase the theoretical WR/O number ratio (long-dashed, dotted for Z=0.004 and 0.001) is also plotted here. At this time the decrease of η_0 with respect to its ZAMS value implies an *overestimate* of the WR/O ratio by typically a factor of $\sim 1.1 - 7.4$ for the metallicities shown here, depending on the exact age of the population

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a correction has, however, not been applied by VC92 and CDC95. To obtain a better quantitative handle on the massive star populations in young starburst galaxies the ideal way is to synthesize directly the relevant observable quantities consistently with stellar evolution models. Such an approach is presented in the following Section.

2. Evolutionary synthesis models for WR galaxies

We have built population synthesis models using the latest Geneva stellar evolution tracks (see Meynet et al. 1994 and references therein) and atmosphere models from Kurucz (1991) for stars with initial masses $M_{\rm ini} < 25 M_\odot$. To obtain a reliable description of the ionizing fluxes of the hot star population we include the recent spectra from the "combined stellar structure and atmosphere models" (*CoStar*) of Schaerer et al. (1996ab) and Schaerer (1996) for more massive main sequence stars. WR stars are described by the theoretical spectra of Schmutz, Leitherer, & Gruenwald (1992). Both the *CoStar* and WR atmosphere models account for non–LTE effects and stellar winds, which has a strong influence on the ionizing flux especially in the He II continuum (see Schaerer et al.).

To study the massive star content in WR galaxies we synthesize the following observational quantities: *1)* Hβ luminosity and Hβ equivalent width accounting for stellar and nebular continuum emission, *2)* nebular He II λ 4686 emission, and *3)* broad WR He II λ 4686 emission feature. The nebular continuum and recombination lines were derived assuming $N_e = 100$ cm^{-3}, $T_e = 10000$ K, and solar H/He abundances (see e.g. Osterbrock 1989). For the WR feature we synthesize the broad He II λ 4686 line in order to compare our predictions with the high resolution observations of VC92, which do not include broad N III and C III blends at $\lambda \sim 4650$[5].
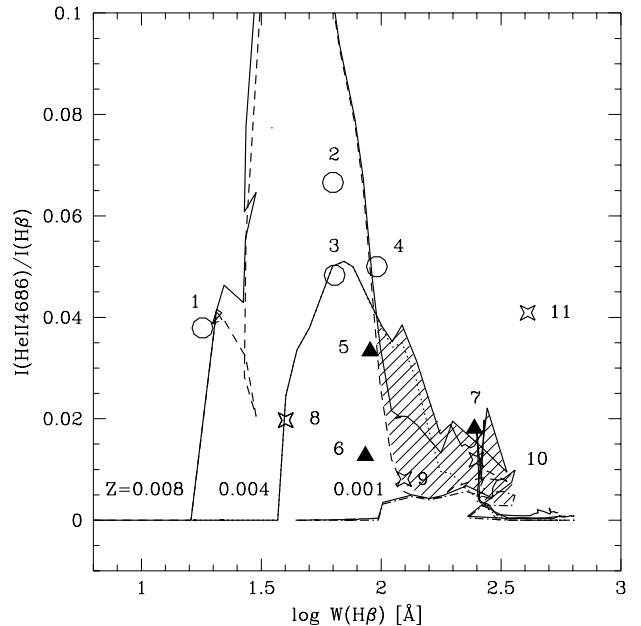

Fig. 2.— Predicted He II/Hβ intensity as a function of the Hβ equivalent width in instantaneous bursts at $Z =0.008$, 0.004, and 0.001. The solid lines include both the nebular He II and the broad WR emission. The dashed, dotted and dash-dotted lines show the pure WR emission. The shaded domain illustrates the region, where a *strong nebular* contribution is predicted. Observations from VC92 and CDC95 are identified as follows. 1: Mrk 1094, 2: Mrk 712, 3+4: NGC 3125 A+B, 5: Tol 35, 6: NGC 1741 B, 7: II Zw 40, 8: He 2-10 A, 9: Mrk 1236 A, 10: Pox 4, 11: Pox 139

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[5]At lower resolution these features, often referred to as the

Consistently with their analysis we adopt an average luminosity of $1.7\,10^{36}\,\mathrm{erg\,s^{-1}}$ for WN stars. WC/WO subtypes have a negligible flux in the He II $\lambda\,4686$ line.

Figure 2 shows the predicted evolution of the (WR+nebular) He II/Hβ intensity as a function of the Hβ equivalent width for instantaneous bursts assuming a Salpeter IMF ranging from 0.8 to 120 $M_\odot$. The results for three metallicities Z are plotted. Correspondingly, the observations by VC92 and CDC95 are grouped into three metallicity "bins": $0.010 > Z \geq 0.005$ (open circles), $0.005 > Z \geq 0.003$ (filled triangles), and $0.003 > Z \geq 0.0025$ (stars). The time evolution proceeds towards low $W(\mathrm{H}\beta)$. At $\log W(\mathrm{H}\beta) \sim 2.5$, the increase of He II/Hβ corresponds to the onset of the WR rich phase of the staburst. Note the strong decrease of the maximum He II/Hβ emission with decreasing Z due to strong dependence of the WR population on metallicity (cf. Maeder & Meynet 1994). In this diagram adopting a flatter IMF would primarily translate to an increase of the He II/Hβ emission at a given $W(\mathrm{H}\beta)$ by increasing the WR emission.

Figure 2 clearly shows that, except for object 11, all observations lie within the range covered by the model predictions. For each metallicity group the agreement is good. Most importantly, the observations for objects 1–5 (see figure caption) which, according to Meynet (1995) and CDC95, would require a very flat IMF ($\alpha \sim 1$) can thus very well be explained with a "standard" Salpeter IMF. Such important deviations from the non-evolving cluster approach are indeed expected, since according to their $W(\mathrm{H}\beta)$ these bursts have ages $t > 4 - 4.5$ Myr (see Section 1.1). Our results confirm the similarly detailed approach of Krüger et al. (1992). They

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"WR bump", are hardly separable. Emission in the WR bump is larger than in the 4686 feature alone, and the behaviour of its time evolution differs both qualitatively and quantitatively from the pure He II 4686 feature modeled in this work (cf. Meynet 1995).

are also in agreement with unpublished observations of other WR galaxies (Vacca, private communication).

Only two objects (8 and 11) seem to disagree with the Salpeter IMF. He 2-10 (object 8), which has a metallicity of $Z \sim 0.003$, might indeed require a somewhat steeper IMF. Pox 139 (object 11) appears as an extreme object in the VC92 sample beacause of its large He II/Hβ ratio at the young age ($t \sim 2.5$ Myr) implied the by high value of $W(\mathrm{H}\beta)$. It must, however, be noted that $W(\mathrm{H}\beta)$ is considerably uncertain due to the very low continuum flux measured in the spectrum of VC92 (Vacca, private communication). The Pox 139 observations of Kunth & Sargent (1983) show a He II/Hβ value lower by a factor of 1.8. Better quality observations would be very useful for this galaxy.

2.1. Nebular He II emission in young starbursts

The presence of nebular He II emission in giant H II regions, requiring a very hard exciting spectrum, appears puzzling (see e.g. Garnett et al. 1991). The use of the latest *CoStar* model fluxes for O stars and appropriate atmosphere models for WR stars (see above) allows us to readdress this question here.

Figure 3 shows the predicted nebular He II/Hβ ratio in instantaneous bursts at different metallicities. First we note that for young bursts we predict typical values of $I(\mathrm{He\,II})/I(\mathrm{H}\beta)$ between $5.\,10^{-4}$ and $2.\,10^{-3}$. Due to the strong He II continuum flux obtained from the O star models, which account for non–LTE effects, line blanketing, and stellar winds (cf. Schaerer et al. 1996b) these values are ~ 4 orders of magnitudes larger than the values which would be derived from other current population synthesis models.

After ~ 3 Myr the He II/Hβ ratio increases due to the appearance of WR stars. The major nebular emission is due to stars in the WC phase. Since these stars have a negligible broad stel-
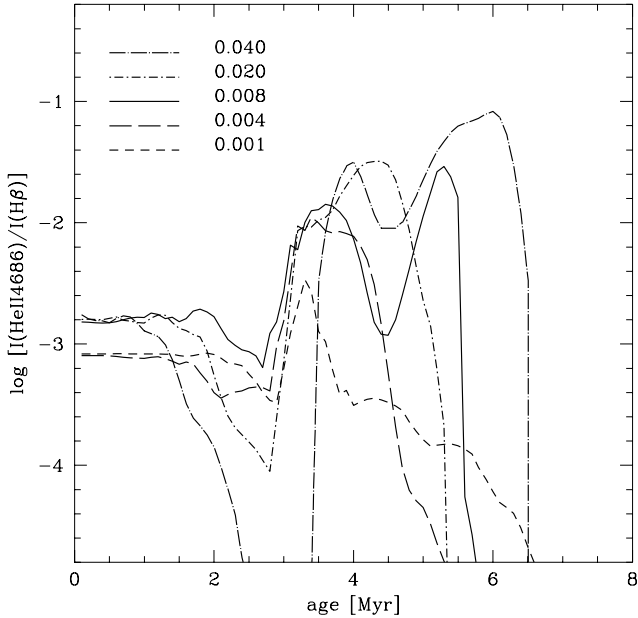
Fig. 3.— Predicted *nebular* emission line ratio of He II/Hβ as a function of burst age for different metallicities (Z =0.001 to 0.04) assuming a Salpeter IMF from 0.8 to 120 $M_\odot$.

lar emission in the 4686 line, we thus expect an *important nebular contribution to the total 4686 emission in the early WC-rich phase.* The domain corresponding to this phase is shown by the hatched area in Fig. 2. Typical values of $I(\text{He II})/I(\text{H}\beta) \sim 0.01 - 0.025$ are attained. At later times (characterized by $W(\text{H}\beta) < 100$ Å in Fig. 2), the broad stellar component from the then important WNL population will dominate the 4686 emission. The strongest relative nebular contribution is predicted between solar metallicity and $\sim 1/5\,Z_\odot$, where in the early WR phase the nebular flux can make up to ~ 75 % of the emission in the He II 4686 line. At $Z > 0.02$ and $Z < 0.004$ the broad WR feature always dominates the 4686 emission[6].

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[6]At high Z the reduction of the absolute Hβ emission overwhelms the increase of the nebular He II/Hβ. At low Z, due to the low mass loss, the WC population becomes

First comparisons with observations show the following: *1)* Two objects in Fig. 2 lie in the domain where the nebular contribution to the total WR+nebular emission is expected to be high. Our prediction is confirmed by inspection of the spectrum of Pox 4 from VC92 (their Fig. 6), which indeed shows an important nebular contribution. We expect a similar nebular contribution in II Zw 40. We note that these objects also show the largest electron temperature in the VC92 sample, which is an additional confirmation of their high excitation. For a more firm conclusion about the excitation conditions in Mrk 712 higher resolution data should be obtained. *2)* Of the 12 objects from Campbell, Terlevich, & Melnick (1986) showing nebular He II emission four (T 1304-353, T 1304-386, C 1543+091, F 30) can well be explained by our models. We suspect that many of the remaining objects might well turn out to show broad He II emission if observed with a sufficient signal/noise (see also Masegosa, Moles, del Olmo 1991). Their three additional objects with broad WR features are also compatible with our models.

3. Summary and outlook

We have shown that methods, which do not account for the evolution of the bursting population will *systematically underestimate* the number of O stars derived from integrated spectra for burst ages $t > 2 - 3$ Myr. As a consequence, present WR/O number ratios in WR galaxies (VC92, CDC95) are thus overestimated. Therefore IMF determinations based on such number ratios will preferentially lead to flat IMF slopes ($\alpha \sim 1$–2; Meynet 1995, CDC95). If one instead properly treats the evolution, the observed massive star population in WR galaxies is compatible with resulting from an instantaneous burst following a Salpeter IMF, in agreement with previous studies using different methods. This con-

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negligible. This explains the dominance of the the broad WR emission for these metallicities.

clusion may, however, need to be revised if other systematic uncertainties (photon leakage, dust, slit positioning etc.; see e.g. Conti 1993) turned out to be important. Obviously it must also be noted that the observed properties are probably not uniquely described by the case of an instantaneous burst discussed here, and that several uncertainties remain (e.g. ionizing fluxes of WR stars).

Using recent stellar evolution models and new spherically expanding non–LTE atmosphere models for O and WR stars, which in particular yield reliable predictions for the ionizing flux in the He II continuum, we have proposed a natural explanation for the observation of nebular He II in extragalactic H II regions and alike objects: High excitation objects should be intimately linked with an important population of WC stars. It is indeed feasible to test this prediction by detecting the broad C IV λ 5808 emission line characteristic of WC stars (see also Meynet 1995). In relatively short phases ($\sim$ 1 Myr) the expected emission (using the WC fluxes from Smith 1991) reaches up to $I(\text{C IV})/I(\text{H}\beta) \sim 0.02 - 0.2$ for metallicities between 1/5 $Z_\odot$ and solar. Similarly, a careful analysis of the C III λ 4650 blend (cf. Krüger et al. 1992) and maybe even the C III λ 5696 line could also be used to measure the WC population.

Although little is presently known about WC stars in starbursts the observations of González-Delgado et al. (1994) showing strong nebular He II emission associated with WC stars support our picture. Future studies should draw their attention on obtaining high quality observations (and providing detection/non-detection limits !) encompassing both the "traditional" WR bump (λ 4650 – 4686) with a sufficient spectral resolution, and the C emission lines. Predicted starburst spectra allowing detailed probes of WN and WC populations will be presented elsewhere (Schaerer & Vacca 1996, in preparation). A systematic study of a large sample of young starbursts, including higher metallicity ob-

jects, will provide crucial tests for stellar evolution and the understanding of star formation processes in these environments.

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